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Air Currents in a Mountain Valley Deduced From the Breakup of a Stratus Deck

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ABSTRACT—A sequence of aerial photographs is presented that illustrates the breakup of a stratus deck that filled the Redwood Creek Valley in northern California on Nov. 4, 1971. The vertical circulation within the valley was deduced from the breakup of the deck: air was rising along the sides of the valley, air was sinking along the center of the valley, and air was moving diagonally away from the center of the valley in a downstream direction connecting the rising and sinking air. This circulation has been suggested in theory, and the rising and diagonal components have been observed. The sinking component, however, has not been observed. The stratus breakup presented in this paper is submitted as evidence that the sinking component exists.

1. INTRODUCTION

Experiments in warm fog (Hindman and Clark 1972) were conducted in the Redwood Creek Valley by the U.S. Naval Weapons Center in cooperation with the Federal Aviation Administration during October and the first week of November 1971. On Nov. 4, 1971, vertical and oblique photographs of the clouds within the valley were taken by a Navy U3 aircraft from an altitude of 3 km above mean sea level. The location of the valley and the areas photographed within the valley are given in figure 1.

Figure 2, two oblique pictures of the same portion of the valley taken 9 min apart, shows a rapid breakup of the stratus along the center of the valley. In this paper we present and interpret the photographs of the breakup, compare the interpretations with existing theories of air currents within a mountain valley, and deduce a probable cause for the breakup.

2. OBSERVATIONS

The weather pattern that dominated the northwestern United States at 0400 PST on Nov. 4, 1971, is illustrated in figure 3. The pressure pattern at the surface and aloft in the region of the Redwood Creek Valley was in the form of a col, with high pressure to the west and east and low pressure to the north and south. In the absence of a strong pressure gradient in the region, light mountain and valley winds developed. Buettner and Thyer (1962) indicate that the mountain wind blows down-valley at night and the valley wind blows up-valley during the day.

The clear skies and light winds in the region permitted significant radiational cooling. Moist air from the ocean is assumed to have penetrated into the coastal valleys in accordance with observations by Burton (1971). The cooling of the moist air led to the formation of the stratus deck in the Redwood Creek Valley. The moist air was not documented because rawinsonde data were not gathered in the valley.

Sunrise in the valley was at 0645 PST. At 0950 PST, the base and the top of the stratus deck were 76 and 152 m above the valley floor, respectively. Wind observations were continuously recorded during the stratus breakup and are presented in figure 4. These data indicated that the average wind between 0800 and 1200 PST was southerly at 0.67 m/s. After 1200 PST, the wind abruptly shifted to the north and the average velocity increased from 0.67 to 2.2 m/s. The valley was approximately 5000 m wide and 700 m deep at the point on the valley floor where the observations were made. That point corresponds to the location of the balloon in figure 1B.

The vertical photographs of the experimental area, (fig. 5) began at 09:51:52 PST on the morning of Nov. 4, 1971. At that time, a hot-air balloon was tethered on top of the stratus deck and is visible in the center of figures 5A–5F. All of the photographs are oriented in the same direction.

The breakup of the stratus deck was barely underway at 09:51:52 PST. The stratus breakup is the depression that extends from the upper left corner to the lower right corner of figure 5A. The forested sides of the valley appear in the upper right and lower left corners. The depression deepened into a clear trough by 09:54:05 PST (fig. 5B). The trough was wider at 10:01:00 PST (fig. 5C) and continued to widen during the remaining observations. The balloon was lowered at 10:01:00 PST and, therefore, is not clearly visible in figures 5D and 5E. The breakup was almost complete by 10:33:03 PST and the balloon is visible on the ground in figure 5F. The stratus was completely dissipated by 10:45:00 PST.

3. DISCUSSION

The clear trough in figure 2 indicates that the stratus deck was evaporating. The width of the trough in figure 5 increased with time, indicating that evaporation was eroding the sides. The evaporation is assumed to have been

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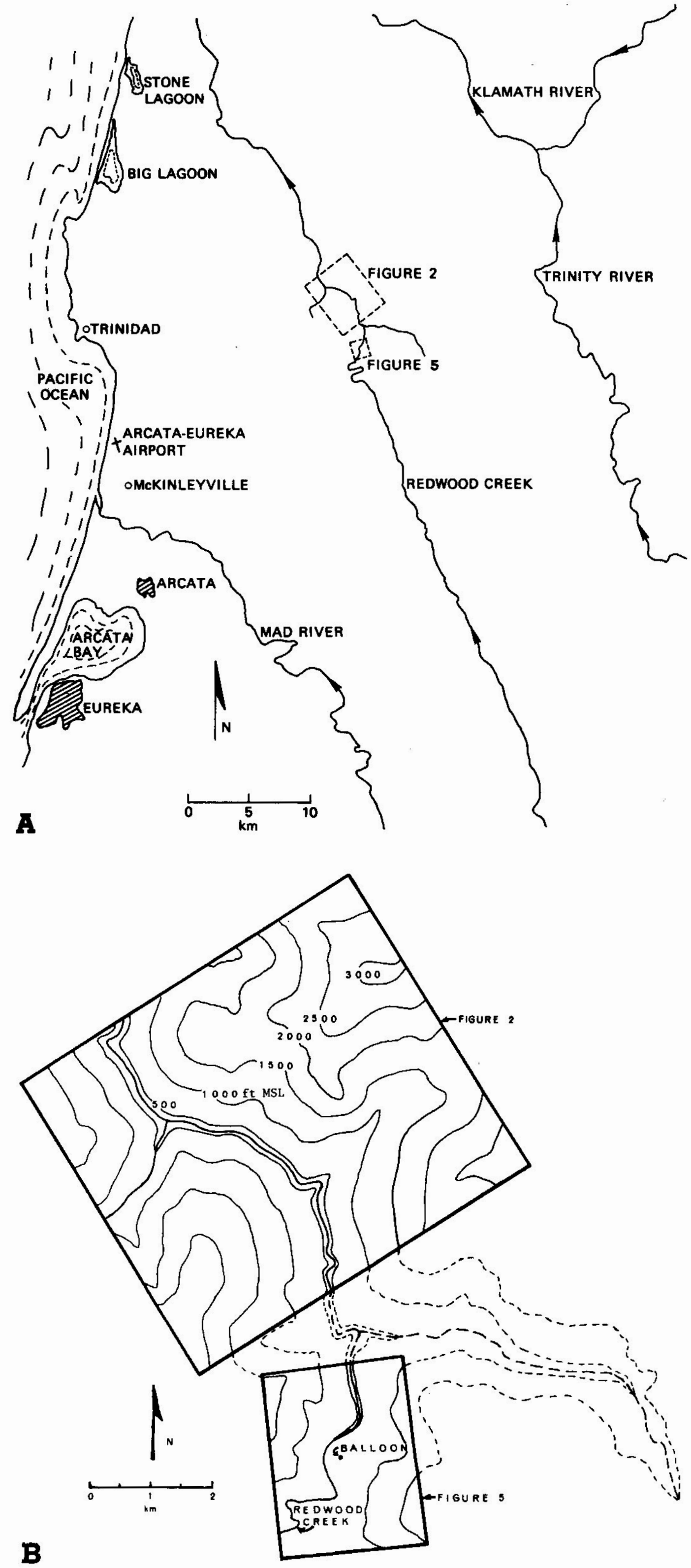

FIGURE 1.—(A) location of the Redwood Creek Valley in which the stratus breakup occurred, and (B) the topography of that portion of the valley pictured in figures 2 and 5. The areas labeled figures 2 and 5 correspond to the oblique photographs in figure 2 and the vertical photographs in figure 5.

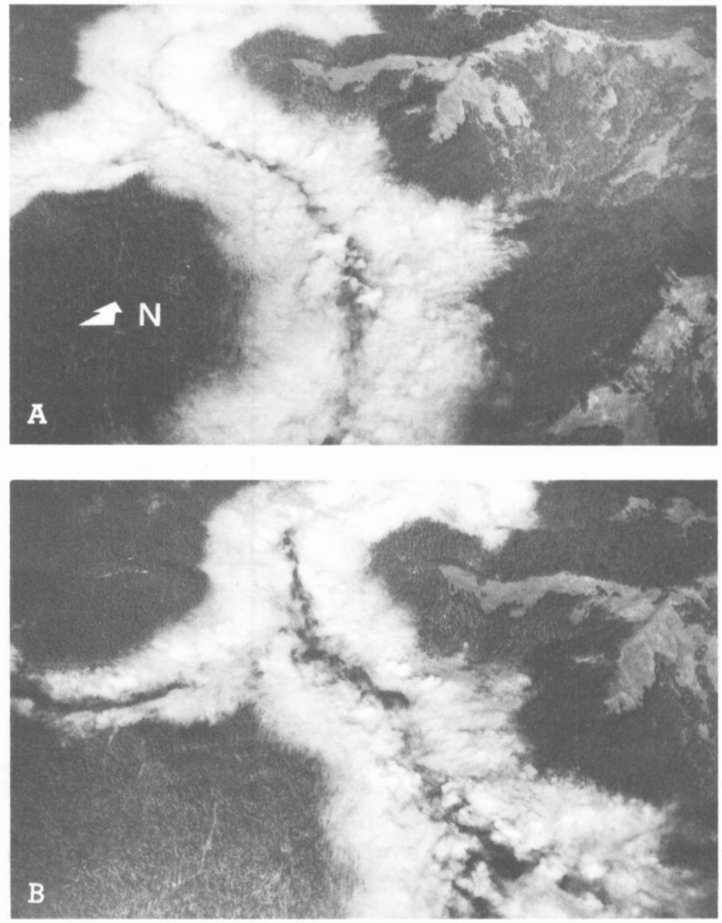

FIGURE 2.—Photographs at (A) 09:58:44 PST and (B) 10:07:40 PST, Nov. 4, 1971, illustrate the stratus deck breaking up in an orderly fashion along the center of the Redwood Creek Valley and along the stream bed intercepting the valley at the left.

caused by the downward induction of dry air adiabatically heated by the descent. The clear trough demonstrates that only the center of the stratus deck was heating. Heating was not taking place within the edges of the stratus deck adjacent to the sides of the valley because the clouds remained the longest at this location (fig. 5F). This pattern of heating required air to rise along the edges and descend in the center as shown in figure 6. The creek and creek bed in the valley floor may have acted as a heat sink as suggested by Munn (1966), enhancing the descent of air and giving the trough the sharp appearance noted in figure 2.

The air currents in a valley during the morning hours have been investigated by Defant (1951). He indicates that shortly after sunrise, air moves up the valley sides and a weak return flow sinks in the valley center, merging vectorially with the mountain wind (fig. 7A). By forenoon (fig. 7B) the mountain wind has ceased, the slope winds are normal to the axis of the valley and stronger, and the sinking air is descending normal to the axis of the valley. Defant suggests the onset of the conditions pictured in figure 7B to be at approximately 0900 LST. He suggests that the valley wind should begin by early afternoon (fig. 7C).

The vertical air currents deduced from the stratus-breakup in Redwood Creek Valley (fig. 6) are in remarkable agreement with Defant's observations (fig. 7B). The breakup of the deck was already underway at the time of the first photograph at 09:51:52 PST (fig. 5A).

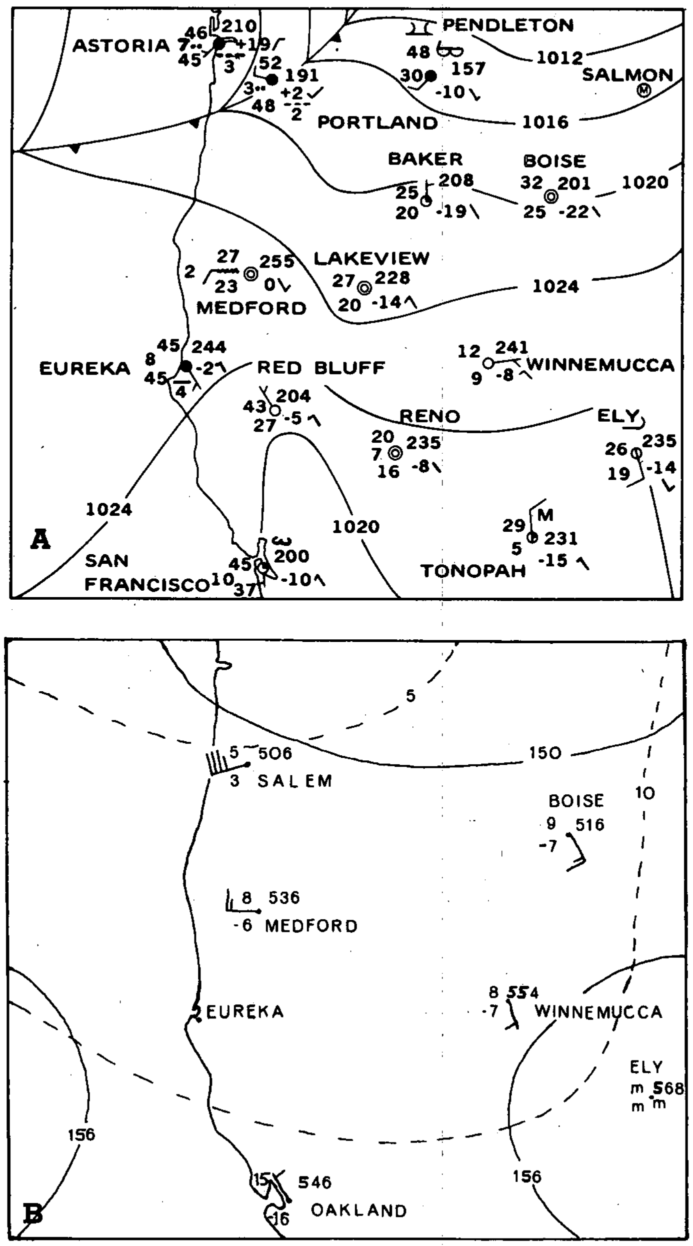

FIGURE 3.—(A) Surface and (B) 850-mb weather maps at 0400 PST, Nov. 4, 1971.

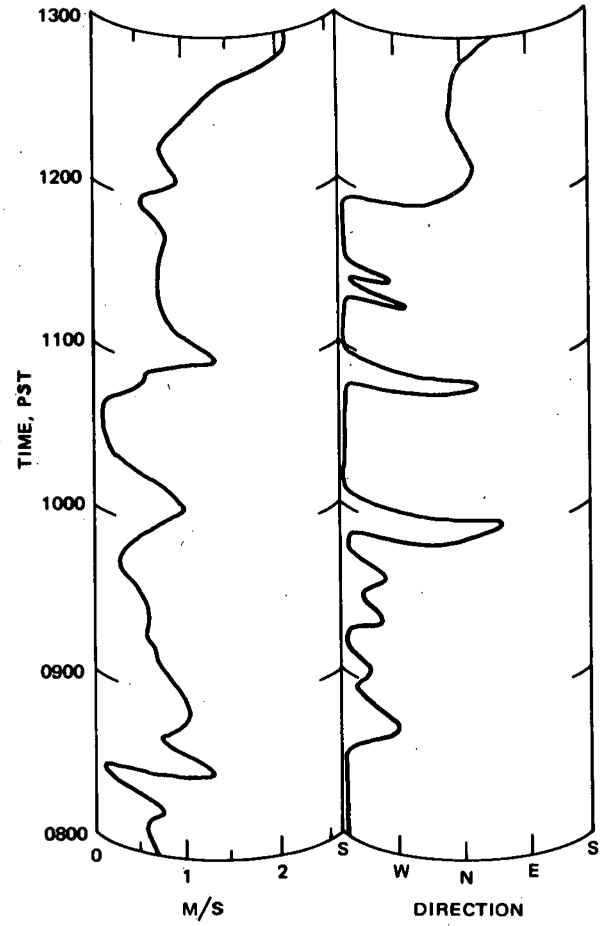

FIGURE 4.—Wind observations in the Redwood Creek Valley on Nov. 4, 1971. The data were provided by the Atmospheric Sciences Laboratory, White Sands Missile Range, N. Mex.

This time agrees well with Defant's suggestion that the vertical circulation should be developed by 0900 LST. The significant mountain wind observed during the breakup of the stratus deck (fig. 4) does not support Defant's suggestion that the mountain wind would be insignificant during the period of maximum vertical motion in the valley. The dramatic onset of the valley wind at 1200 PST, however, does support Defant's observation depicted in figure 7C.

Defant (1951) has estimated how long it would take the rising heated slope air to replace the air mass over a valley bottom. This process of warming the air in a valley center is important because the warming affects the pressure gradient between the valley and the plains and thus the generation of the mountain and valley winds. Defant's calculations showed that a volume of air 1 m thick, 1500 m long (width of his valley), and 1750 m high

TABLE 1.—*Calculation of the rate of increase of the clear trough in figure 5*

Time of photograph	Δ Time	Trough width	Δ Width	Rate of increase
(PST)	(min)	(m)	(m)	(m/min)
09:51:52		210		
	2.2		30	13.7
09:54:05		240		
	6.9		130	18.9
10:01:00		370		
	11.0		180	16.4
10:11:57		550		
	10.8		150	13.9
10:22:46		700		
	10.3		210	20.2
10:33:03		910		
				16.6*

* Average.

(depth of his valley) is completely replaced in a closed circulation by heated slope air in 4.5 hr. Using Defant's valley, we estimated a replacement rate (m^3/min) by multiplying the volume's thickness by its width and depth and dividing by 270 min. This calculation resulted in a rate of $1.0 \times 10^4 m^3$/min.

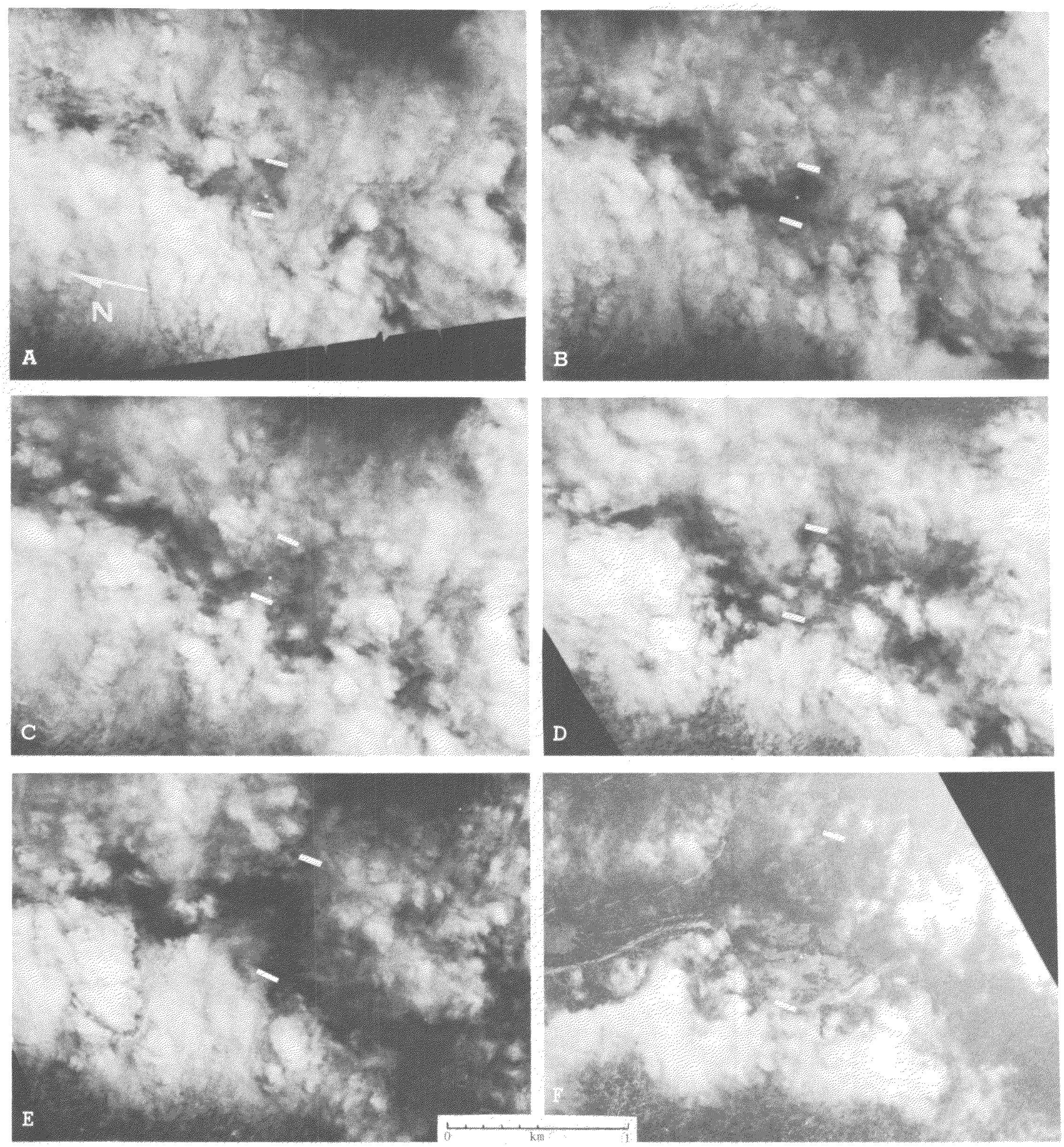

FIGURE 5.—Photographs at (A) 09:51:52 PST, (B) 09:54:05 PST, (C) 10:01:00 PST, (D) 10:11:57 PST, (E) 10:22:46 PST, and (F) 10:33:03 PST' Nov. 4, 1971, from the Navy U3 flying at 3000 m MSL above the Redwood Creek Valley. The manned hot-air balloon is in the center of each picture. The breakup of the stratus deck is the diagonal clear trough from the upper left corner to the lower right corner in each picture. The white marks on either side of the balloon show the estimated width of the trough.

The replacement rate during the observed stratus breakup was calculated using the dimensions of the Redwood Creek Valley (5 km wide and 700 m deep) and the period of time from sunrise to the complete evaporation of the deck (4 hr). In this time period, it was assumed that the heated slope air had replaced the air in the valley. A replacement rate of $1.4 \times 10^4 m^3/min$ was calculated from these observations.

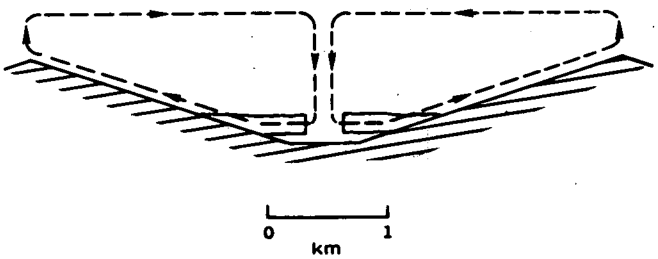

FIGURE 6.—Schematic illustration (to scale) of the vertical air currents in the Redwood Creek Valley with the stratus deck depicted realistically in the valley bottom. The directions of the currents were deduced from figures 2 and 5.

Another method was employed to calculate the replacement rate. The average rate that the trough along the center of the valley increased in width was estimated from figure 5. The width normal to the axis of the trough was measured from each photograph at the position of the balloon. The change in width between two consecutive photographs divided by the time interval between the photographs defined the rate at which the trough increased in width. This rate was calculated for each pair of photographs. The rates were averaged, resulting in a rate of 16.6 m/min (table 1). The replacement rate was then calculated by multiplying the average rate by the depth of the valley. The calculation resulted in a replacement rate of $1.2 \times 10^4 m^3$/min. The value supports the 1.4×10^4 value previously calculated using the observed length of time from sunrise for the complete evaporation of the stratus deck. The agreement between the replacement rate calculated from Defant's data and the two rates calculated from the stratus breakup indicates that the replacement rate in a mountain valley is on the order of $10^4 m^3$/min and the time period from sunrise for complete replacement is on the order of 4 hr.

Buettner (1967) reported results from a numerical simulation model of the circulations within a mountain valley. The results vary from the simple theory of Defant (1951). Nevertheless, the calculations of Buettner (fig. 8A) support the concept of vertical air currents envisioned by Defant (fig. 7B). Buettner states that "the descending vertical component in midvalley below the ridge level has (without mathematical proof) also been claimed by Defant (1951), but as far as is known has never been observed." [1]

The observation of the stratus breakup in figures 2 and 5 is submitted as evidence that this postulated descending vertical component in midvalley does exist. Furthermore, the slope-wind speed computed by Buettner is on the order of 0.2 m/s (fig. 8B). The slope wind during the stratus breakup is assumed to be represented by one-half the rate that the trough increased in width or 0.14 m/s. The agreement between slope-wind calculated by Buettner and the slope-wind calculated from the stratus breakup is submitted as evidence that Buettner's value is of the proper order.

[1] Wagner (1932) postulated the descending vertical component through theoretical considerations and undocumented visual observations of cloud dissipations in mountain valleys.

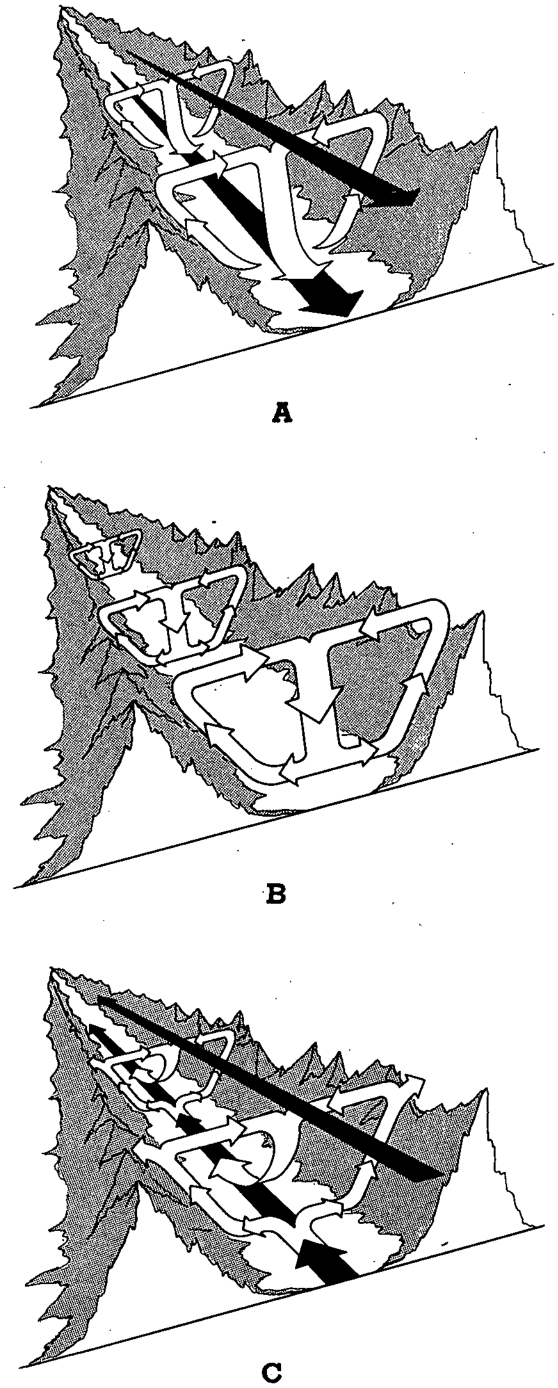

FIGURE 7.—Schematic illustration of the air currents in a valley at: (A) Sunrise; onset of upslope winds (white arrows) and continuation of mountain wind (black arrows) with valley cold and plains warm, (B) Forenoon (about 0900 LST); strong upslope winds (white arrows) and transition from mountain wind to valley wind with valley temperature same as plains, and (C) Noon and early afternoon; diminishing slope winds (white arrows) and fully developed valley wind (black arrows), with valley warmer than plains. [Adapted from a figure by Defant (1951).]

Since the slope-wind component appears reasonable, Buettner's calculated descending vertical component of 0.25 m/s may also be realistic (fig. 8A). Buettner rejected this magnitude because he did not observe any significant descending air 400 m above the ridge top. Perhaps the descending current did not originate this high. He calculated, however, the maximum descending component to

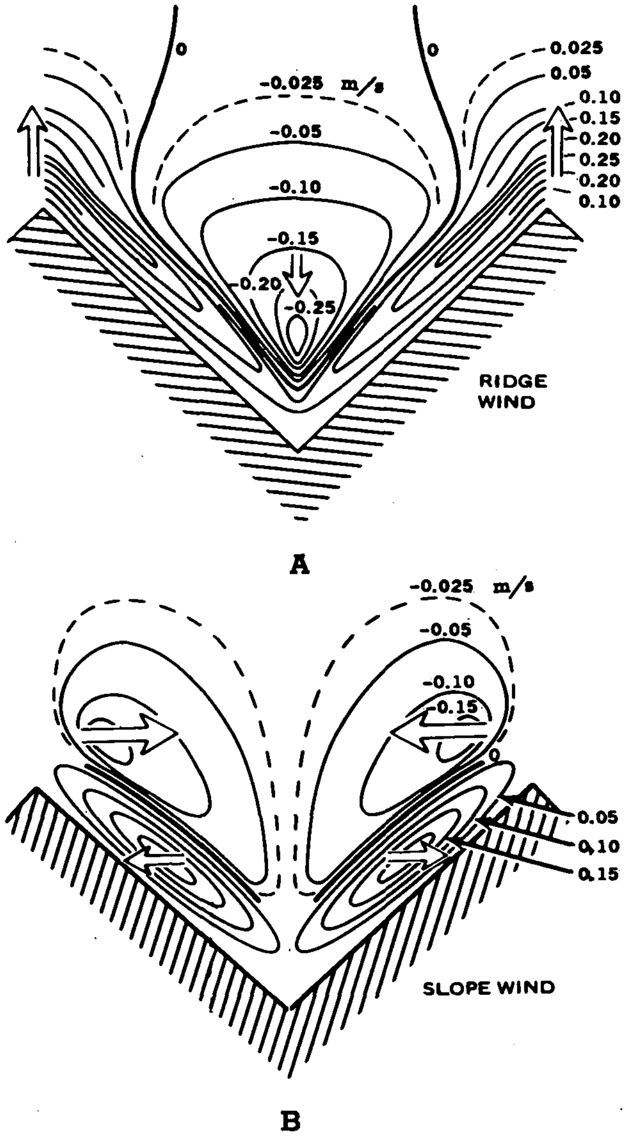

FIGURE 8.—The results (m/s) from a numerical simulation model of mountain and valley winds (Buettner 1967) approximately 2 min after the start of the heat input ("sunrise").

be at the bottom of the valley. The stratus deck in figure 2 is in the bottom of the valley. The descending air deduced from the stratus breakup, therefore, supports the descending vertical component calculated by Buettner.

4. CONCLUSIONS

The breakup of the stratus deck observed in the Redwood Creek Valley on Nov. 4, 1971, demonstrated the following circulation within the valley: air ascending along the heated slopes, air descending along the center of the valley, and air moving diagonally away from the center of the valley connecting the descending and ascending currents. This observation supports the circulation patterns reported by Defant (1951) and Buettner (1967).

The following information resulted from analysis of the stratus breakup. The length of time from sunrise for the rising slope air to replace the valley air was found to be 4 hr. The rate the air was replaced was on the order of $10^4 m^3/min$. Both these results are in agreement with similar observations made by Defant (1951). The magnitude of the slope wind was found to be 0.14 m/s, similar to the 0.2 m/s computed by Buettner (1967). This similarity suggests that the descending component calculated by Buettner ($\approx$0.2 m/s) may be the magnitude of the descending component, which could not be calculated from the stratus breakup. The fact that the mountain wind persisted during the period of maximum vertical circulation [also observed by Buettner (1967)] suggests that the cessation of the mountain wind during the period, as envisioned by Defant, may not occur.

REFERENCES

Buettner, Konrad J. K., "Valley Wind, Sea Breeze, and Mass Fire: Three Cases of Quasi-Stationary Airflow," *Proceedings of the Symposium on Mountain Meteorology, Fort Collins, Colorado, June 26, 1967*, Department of Atmospheric Science, Colorado State University, Fort Collins, **1967**, pp. 103–129.

Buettner, Konrad J. K., and Thyer, Norman, "Valley Winds in Mt. Rainier National Park," *Weatherwise*, Vol. 15, No. 2, Apr. **1962**, pp. 63–67.

Burton, Robert E., "A Weatherman Looks at the Redwood Tree: California's Fog Drinker," *Weatherwise*, Vol. 24, No. 3, June **1971**, pp. 120–124.

Defant, Friedrich, "Local Winds," *Compendium of Meteorology*, American Meteorological Society, Boston, Mass., **1951**, 1334 pp. (See pp. 655–672.)

Hindman, Edward E. II, and Clark, Richard S., "Evaluation of Warm-Fog Abatement Chemicals," *Final Report* No. FAA–RD–72–21, Dept. of Transportation, Federal Aviation Administration, Washington, D.C., Feb. **1972**, 31 pp.

Munn, R. E., *Descriptive Micrometeorology*, Academic Press, New York, N.Y., May **1966**, 245 pp.

Wagner, A. von, "Neue Theorie Des Berg-Uno Talwindes," *Meteorologische Zeitschrift*, Band 49, Heft 9, **1932**, pp. 329–341.

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